Met Office

Can we improve plume dispersal modelling for fire related emergency response operations by utilising short-range dispersion schemes?

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Abstract

Large fires that produce plumes of smoke and other contaminants can cause harm to both people and the environment. To support UK emergency responders, the Met Office Environmental Monitoring and Response Centre (EMARC) provides dedicated weather advice and forecasts of the plume in the form of CHEmical METeorological (CHEMET) reports. The plume's expected location, extent and relative air concentrations of pollutants are predicted using the Numerical Atmospheric-dispersion Modelling Environment (NAME), which simulates the transport and dispersion of pollutants using numerical weather prediction data. During major fires, air quality monitoring equipment is deployed to confirm the presence of elevated concentrations of contaminants. We use ground-level air concentration measurements from multiple events to evaluate the operational set-up of NAME. We investigate both the output averaging depth used to calculate air concentrations and the use of three optional NAME schemes that are designed to improve the representation of short-range dispersal dynamics: the near-source scheme, the plume-rise scheme, and the urban scheme. We find that using the current operational output averaging depth of 100 m produces model air concentrations that compare best to point observations at the surface, and that using the near-source and urban schemes further improves the fit. However, using these more computationally expensive schemes has little impact on the modelled location and extent of the plume, suggesting they may offer no advantage over using the current operational set-up to produce CHEMETs. Using the plume-rise scheme strongly influences the predicted plume location, extent and surface concentrations. Further work is needed to understand whether its application is appropriate for simulating plumes from fires. We conclude that the current operational set-up can be maintained while the significance of the impact the optional schemes have on CHEMET plume dispersal forecasts is considered further.

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1. Introduction

Incidents which produce plumes of smoke and other contaminants, such as fires and chemical leaks, can cause harm to both people and the environment. The Met Office Environmental Monitoring and Response Centre (EMARC) provides dedicated weather advice and plume dispersal forecasts in the form of CHEmical METeorological (CHEMET) reports to emergency responders in the UK, to help mitigate the risks. The forecasts included in these reports indicate the plume's expected location and relative air concentration, while additional 'pro' forecasts display quantitative air concentrations, dosages and time integrated deposition over the requested forecast period.

The plume dispersal forecasts are produced using NAME, the Met Office's Numerical Atmospheric-dispersion Modelling Environment (Jones et al. 2007, Leadbetter et al. 2010). Operationally, NAME uses a Lagrangian approach to simulate the atmospheric transport and dispersion of many model particles, representing the material released, using Numerical Weather Prediction (NWP) data from the global version of the Met Office's Unified Model (MetUMG, Walters et al. 2019) and the higher resolution UK limited area configuration (UKV, Tang et al. 2013, Bush et al. 2020, Bush et al. 2023). During most incidents, exact details of the release are unknown so default source terms representing common scenarios are used in the NAME simulations: a unit release (1 g s^{-1}) of a tracer substance from a vertical line source 0 – 10 m agl (above ground level) with a uniform distribution. If extra information becomes available during an event, then more exact descriptions can be provided to model the release as a cubic source of a specific amount of a particular substance.

If an event is deemed to meet 'major incident' criteria and there is significant potential risk to public health and the environment due to emissions from the incident, an Air Quality Cell (AQC) may be activated to provide a national, multi-agency incident management service to assess air quality and coordinate the provision of timely advice on public health impacts (Barker 2010, Griffiths et al. 2018., Environment Agency 2022). The Environment Agency (EA) lead AQC activities, with key partners including the UK Health Security Agency (UKHSA), the Met Office, the Food Standards Agency (FSA) and the Health and Safety Executive (HSE). The AQC has responsibility for procuring and assessing real-time air quality monitoring data and detailed dispersion modelling to assist incident managers in making decisions pertaining to evacuation, sheltering and exposure and to inform future monitoring and modelling actions.

While previous studies have looked at the health impacts of past incidents using AQC monitoring data (Izon-Cooper 2010, Brunt and Russel 2012, McParland and Paranthaman 2012, Lamb et al. 2013, Leadbetter et al. 2014, Morrow and Mitchem 2014, Landeg-Cox et al. 2015, Griffiths et al. 2018), few discuss the accuracy of the modelled CHEMET plumes. Furthermore, CHEMETs themselves do not currently utilise any of the optional NAME parameterisations that have the potential to more accurately represent short-range processes that affect the scales and situations over which CHEMETs are produced. Previously, these schemes have only had their modelling capability assessed against non-AQC events and field experiments (Webster and Thomson 2002, Webster et al. 2006,

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Webster et al. 2011, Hernández-Ceballos et al. 2019a, 2019b, Kendall et al. 2019a). In this study, we use monitoring data available from a selection of AQC events to investigate whether our current operational set-up is still appropriate or whether improvements can be made.

Between April 2009 and March 2016, 74% of AQCs were the result of fires at waste management facilities (Griffiths et al. 2018). Here we assess NAME dispersal forecasts for five waste fire AQC events by comparing the predicted location, timing, and relative concentration of pollutants to the monitoring data obtained for each incident. We first examine the effectiveness of our current operational set-up, including the output averaging depth used to calculate forecast air concentrations. Then we introduce four new set-ups that use a combination of short-range dispersion schemes in NAME and consider whether they improve the forecasts.

We begin by outlining three NAME schemes that are designed to improve the representation of dispersion dynamics over similar short-ranges that CHEMETs are issued for: the near-source scheme, the plume-rise scheme, and the urban scheme. Then we describe the methodology of our investigation, including a summary of our case-study AQC events and how we represent them in NAME, an explanation of the monitoring data used and how they have been processed, and a description of the NAME settings used to best compare output to the monitoring data. The statistics used to assess the performance of each of the set-ups are described prior to examining the results from our study, focussing on a couple of events in detail before looking at the overarching results and conclusions from across the whole study.

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2. Short-range NAME Schemes

2.1. Near-Source

The near-source scheme in NAME (Jones et al. 2023b) is a random-walk scheme designed to improve the representation of local turbulence over short distances by using a Langevin approach velocity-memory scheme that also accounts for inhomogeneous turbulence within the boundary layer. The change in a particle's turbulent velocity becomes dependent on its current turbulent velocity and thus correlated in-time, so long as it remains within the inhomogeneous boundary layer. This leads to more realistic particle spread close to the source. The random-walk processes of the mesoscale motion parameterisations of NAME also have a velocity-memory scheme to similar effect. In this study, when the near-source scheme is used, it includes the velocity-memory scheme for inhomogeneous turbulence profiles and the velocity-memory scheme for mesoscale motions.

2.2. Plume-Rise

The plume-rise scheme in NAME (Webster and Thomson 2001, Webster and Thomson 2002, Jones et al. 2023a) uses the conservation equations of mass, momentum, and heat to model the initial rise of a plume due to buoyancy and momentum effects. While the scheme was designed to model plumes from power station stacks and similar industrial releases, it can and has been used to model releases from fires (Webster, et al. 2006, Webster et al. 2011, Kendall et al. 2019a, 2019b), with the understanding that some of the assumptions made by the scheme might simplify the representation of a plume originating from a fire. The underlying integral model is solved separately for each model particle until it is considered to be passive, after which it follows the ambient motion of the air, thus allowing the rise of each particle from the source to respond to local conditions individually. Assuming that the plume consists mostly of hot air, the buoyancy and momentum are dependent on the temperature difference between the plume and ambient air, the velocity of the effluent compared to the ambient flow, and the plume radius. As such, some knowledge of the release temperature and flow velocity or volume flow rate at the source, along with the size and height of the source, is required to use the scheme. To ensure that appropriately small time-steps are used for the plume-rise calculations, the near-source scheme should also be invoked.

For this study, we estimate the release temperature and flow velocity of each fire using HSE's Source Term Estimation Programme (STEP). STEP was developed for the EA for use in major incident fires to rapidly estimate source terms and emission rates that can be used with dispersion models such as NAME to inform decision making on potential health impacts. It therefore follows that we should use the same tool to mimic the information the Met Office may be provided during a real incident. STEP uses information on the fire type, size, and duration, along with the total flammable load to characterise and calculate source term details. The source temperature and buoyancy flux are prescribed based on the details

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provided, while the source term velocity, heat release rate and species emission rate estimates are calculated for each event.

2.3. Urban

The urban canopy can influence flow and dispersion in two main ways: the heat balance in urban areas is significantly perturbed with reduced evaporation and the addition of heat storage and sources within the city fabric; and the flow is altered by the presence of buildings, both within and above the urban canopy. When using MetUMG or UKV data, the urban effects on the heat balance are modelled and the effect of the buildings on the momentum of the boundary layer above the canopy is treated through an enhanced roughness length, but the altered mean flow and turbulence within the canopy itself is not well represented. The NAME urban scheme (Thomson et al. 2024) is designed to address this issue by altering the vertical profiles of mean flow and turbulence using a parameterised approach that treats the canopy as statistically homogeneous over ‘neighbourhood’ scales. The urban canopy is described using the mean urban canopy height, fractional building plan area, fractional building frontal area, and building length scale to inform the parameterisations. The building length scale corresponds to the street canyon length and is assumed to be 100 m in NAME, while the other values can either be provided directly to NAME or estimated from urban land-use fraction ancillary data when using NWP meteorological data. The overall effect of the urban scheme is to generally reduce wind speeds and thus increase crosswind spread. To adequately represent the smaller scale dispersion across the depth of the urban canopy, the near-source scheme should again be used to make use of the smaller time-steps it implements. In this study, the urban canopy information is estimated using urban land-use fraction data from the UKV, which comes from the International Geosphere-Biosphere Programme dataset (Loveland et al. 2000, Walters et al. 2019, Bush et al. 2020) and all sites exceed the minimum NAME urban scheme activation threshold of an urban land use fraction > 0.05.

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3. Methodology

3.1. AQC Event Selection and Details

To ensure that both the plume-rise and urban schemes could be assessed along with the near-source scheme, we selected AQC events that involved fires at waste management or storage facilities located close to urban populations. We also only selected events where adequate information was available to model a plume in NAME, namely if the incident and monitoring locations were well defined and if the fire's approximate duration and size were known. The five chosen events are described below with key details compiled in Table 1 and mapped locations shown in Figure 1. Additional information was obtained from meeting reports and notes taken during the incidents and through correspondence with colleagues at UKHSA. Approximate source dimensions were determined using satellite imagery of the sites compared to photographs taken during the events.

Table 1: Event and source term details for each case study AQC.

AQC Event	Swansea	Kidderminster	Smethwick	Swindon	Sunderland
Location	-3.984267, 51.643235	-2.264663, 52.360895	-1.970482, 52.502965	-1.758811, 51.568671	-1.398694, 54.914838
Start Date	16/06/2011 12:00 UTC	16/06/2013 16:30 UTC	30/06/2013 22:00 UTC	21/07/2014 17:00 UTC	14/05/2018 17:00 UTC
Approximate Fire Duration	532 hours	1,300 hours	120 hours	1,344 hours	496 hours
Type of Fire	Building	Building	Open	Open	Building
Estimated Fire Load	5,000 tonnes	4,930 tonnes	10,000 tonnes	5,000 tonnes	30,000 tonnes
Approximate Source Dimensions	100 x 95 x 3 m (110 m diameter)	205 x 40 x 9 m (100 m diameter)	20,000 m^2 x 5 m (160 m diameter)	4,000 m^2 x 9 m (70 m diameter)	80 x 65 x 4 m (80 m diameter)
STEP Source Term Velocity	0.23810 m s^{-1}	0.71429 m s^{-1}	2.38095 m s^{-1}	2.38095 m s^{-1}	0.31746 m s^{-1}
STEP Source Temperature	150 °C	150 °C	150 °C	150 °C	150 °C
STEP Heat Release Rate	285 MW	738 MW	6,000 MW	1,200 MW	208 MW
STEP PM_{10} Emission Rate	57.44 g s^{-1}	23.18 g s^{-1}	1,018.52 g s^{-1}	113.67 g s^{-1}	3,669.62 g s^{-1}
# Monitoring Datasets	7	3	4	6 (from 4 locations)	4

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Swansea

A fire at an unoccupied warehouse storing waste tyre material in Fforestfach, Swansea started around midday UTC on 16 June 2011 and lasted until 8 July 2011. The fire produced a thick, dark plume throughout the burning period which was observed to reach 60 – 70 m (agl) by a member of the public. The air quality monitoring data, provisioned by the AQC that was activated, were used to advise decision-making on sheltering, public building closure, and evacuation (BBC News 2011a, 2011b, Brunt and Russel 2012).

Kidderminster

On 16 June 2013 a large fire broke out at a recycling facility in Kidderminster at 5:30 pm BST, leading to road closures and the issuance of advice to keep doors and windows closed. It was the second fire at the same facility in a 6-month period (Kidderminster Shuttle 2013).

Smethwick

A fire broke out at approximately 11 pm BST on 30 June 2013 at a recycling depot in Smethwick, involving approximately 10,000 tonnes of baled plastic and paper waste. The plume was observed to be elevated during much of the event, with a police helicopter estimating plume heights between 700 – 2,000 m (agl), but due to nearby sensitive receptors an AQC was run from 1-2 July. Monitoring teams were deployed, roads and schools near to the fire were closed, and shelter-in-place messages were issued (BBC News 2013, Leadbetter et al. 2014, Morrow and Mitchem 2014).

Swindon

The fire that broke out at a Swindon recycling facility at 6 pm BST on 21 July 2014 was the first event for which two AQCs were activated, with monitoring data requested for both. This was in part due to the length of the event, changes in the firefighting regime and the level of media attention it received. The first AQC ran from 22-23 July, while the second, which we study here, ran from 27-28 August, with the fire finally being extinguished on 15 September. The fire took eight weeks to put out due to the large volume of compacted waste and a lack of physical space for the fire fighters to tackle the blaze (BBC News 2014a, 2014b, 2014c, 2014d, Landeg-Cox et al. 2015).

Sunderland

At 6 pm BST on 14 May 2018 a large fire broke out at a disused recycling plant in Sunderland, creating a large plume of smoke. More than 30,000 tonnes of mixed industrial and domestic waste were involved making it challenging to handle (BBC News 2018a, 2018b).

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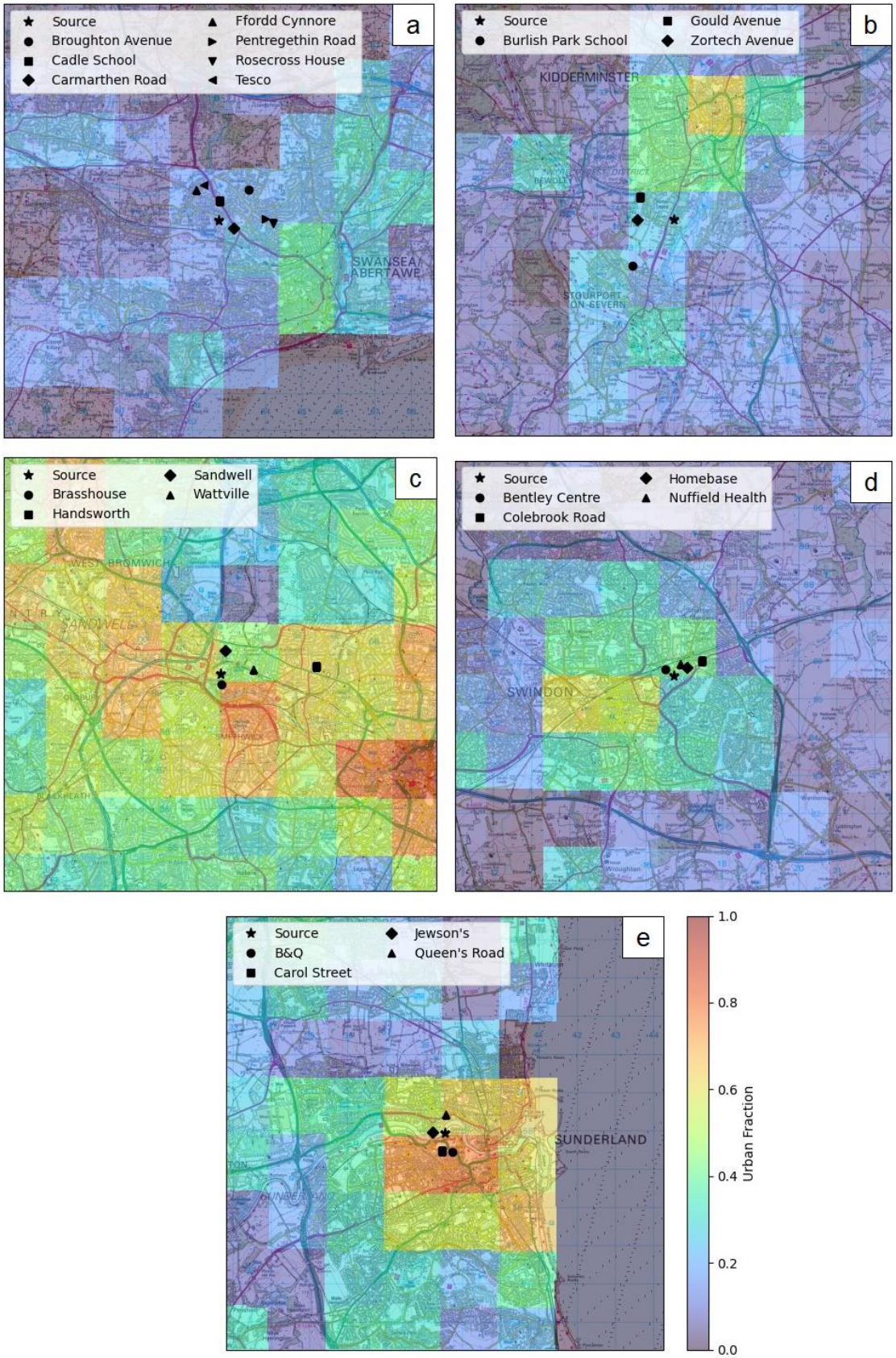

Figure 1: Annotated maps showing the location of each event and the monitoring locations used in this study overlaid with the UKV urban fraction values used by the NAME urban scheme for a) Swansea, b) Kidderminster, c) Smethwick, d) Swindon, and e) Sunderland.
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3.2. Monitoring Data Selection and Processing

When air quality monitoring is requested during an AQC, this service is typically provided by contracted incident response teams using portable equipment and a mobile laboratory trailer over a few days (Barker 2010, Griffiths et al. 2018), but it can sometimes be supplemented by longer-term monitoring from local authorities (Brunt and Russel 2012, Landeg-Cox et al. 2015). As a result, the monitoring equipment used, and the substances monitored, can vary. Observed particulate matter air concentrations (PM_{10}, $PM_{2.5}$ and PM_1) were available for all the events at multiple locations so we have chosen to compare the PM_{10} data to NAME output. To ensure a consistent frequency of observations across the different sites and events, the monitoring data were further processed into 15-minute averages, following Griffiths et al. (2018). The monitoring data for the events studied were sourced from the EA and the locations they were measured at can be seen in Figure 1.

3.3. Model Set-up

We compare the performance of the operational NAME set-up for CHEMETs to set-ups using the selected NAME schemes by running multiple simulations for each event, all using the same 1.5 km resolution hourly UKV NWP data. The ‘default’ set-up is based on our operational set-up, with some small changes to: the particle release rate (# Particles) and the maximum number of model particles (Max # Particles), to account for longer simulation durations so that model noise does not increase; the source shape and particle sync time, to reduce differences to the set-ups using the short-range schemes that require different options to function; and the output grids, to evaluate the current operational settings and compare to monitoring data. The operational range of the input parameters and those used in the ‘default’ set-up are described in Table 2. The set-ups using the short-range schemes use the ‘default’ set-up as a base with combinations of the three schemes additionally turned on: the ‘near-source’ set-up has only the near-source scheme turned on; the ‘urban’ set-up has the near-source and urban schemes turned on; the ‘plume-rise’ set-up has the near-source and plume-rise schemes turned on; and the final set-up called ‘all’ has all three schemes turned on.

A smaller sync time is used to ensure that the time-steps determined by the near-source scheme remain small enough for the urban and plume-rise schemes. A cylindroid source is used because the plume-rise scheme requires a circular source, meaning the horizontal source dimensions for each event are converted into diameter equivalents, based on the total calculated source area (Table 1). When using the plume-rise scheme, a single source height, from which the particles are released and transported upwards, must also be defined and is here taken from the vertical source dimension of each event. In the ‘default’, ‘near-source’ and ‘urban’ set-ups, particles are instead released from a defined plume depth. Because there are few observed plume heights for the events, the default operational release depth of 0 – 10 m agl is used for all events for consistency. STEP derived source term velocities and temperatures are used by the set-ups using the plume-rise scheme, but

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a unit release (1 g s^{-1}) of PM_{10} is used for all NAME simulations so that STEP derived emission rates can be assessed separately once the modelling has been completed. For the simulations which use it, the near-source scheme is kept on for the duration of each particle's travel time. The urban fraction ancillary data, seen in Figure 1, is only used by the 'urban' and 'all' set-ups to inform the urban scheme parameterisations.

Table 2 describes the gridded field output produced as hourly averages over three different averaging depths: 0 – 10 m agl, 0 – 100 m agl and over the boundary layer (BL) depth, in order to visualise the spatial spread of the plumes in relation to all the monitoring locations and the local urban areas. An hourly average is used because this is the shortest output period used operationally. Timeseries of air concentration data are also produced at each of the monitoring locations to better compare the NAME forecasts to the monitoring data. They are comprised of 15-minute averages over the same three depths as the gridded data, to match the temporal resolution of the observation data and determine which output averaging depth best represents ground-based measurements.

Table 2: Values of NAME input parameters used in this study vs the range of operational values.

NAME Setting	Study Input Value	Operational Range
Source Shape	Cylindroid	Cuboid
Source Strength	1.0 g s^{-1}	> 0.0 g s^{-1}
# Particles	600,000 hr^{-1}	250,000 – 600,000 total
Max Particle Age	Infinity	Infinity
Dispersal Domain	0.18x0.11 degrees (~12x12 km)	0.18x0.11 – 2.88x1.76 degrees (~12x12 km – ~192x192 km)
Z Max	8 km	8 km
Max Travel Time	Infinity	Infinity
Max # Particles	2,000,000	1,000,000
Sync Time	00:00:10	00:00:20
Field HGrid	~60x60 m in 200x200 grid	~60x60 – ~960x960 m in 200x200 grid
Timeseries HGrid	~12x12 m	N/A
Output ZGrids	0 – 10 m agl, 0 – 100 m agl, BL	0 – 100 m agl
Field Output	Hourly averages with 10 s contributions	Average over 1 – 72 hours with 20 s contributions
Timeseries Output	15-minute averages with 10 s contributions	N/A

3.4. Evaluation Methods

To assess the accuracy of the modelled air concentrations produced using each of the NAME set-ups we use several statistical methods to compare the modelled and observed air concentrations of PM_{10} at each monitoring location for every event. The chosen statistics

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look at different aspects of the forecast accuracy to evaluate whether the overall trend, variability, and relative magnitude of the observations can be captured when using the different NAME set-ups. To assess the results independently of any artificial biases caused by using a unit release, all the model outputs are scaled to the observations before the statistics are calculated. These scaling factors are also compared to the STEP estimated emission release rates to assess the usability of the emission rate estimates. The chosen statistics and the method of determination of the scaling factor are described below:

Scaling Factor

Scaling factors, *SF*s, are applied to the model timeseries data in order to compare the statistics from different set-ups without the scale variability of the model output produced using the different set-ups and output averaging depths artificially introducing scale biases when the actual emission rate is unknown. A different *SF* is calculated for each of the set-up and output averaging depth combinations at each monitoring location by comparing the temporal mean of the observation data (C_O) to the temporal mean of the model data (C_M).

$$SF = \frac{\overline{C_O}}{\overline{C_M}}$$

In the case where a monitoring location has observations from multiple sources, separate SFs are calculated for each source.

Correlation

Correlation, *R*, is a measure of the linear relationship between two sets of data. If the higher magnitude values of one dataset completely align with the higher magnitude values of the other set, and the same is true of the lower magnitude values, then the correlation will equal 1. If higher magnitude values align with lower magnitude values, then the correlation will equal -1 and the two datasets are negatively correlated. A value of zero indicates no linear relationship between the two datasets. This can be used to see how well the general temporal trend of the observed and modelled air concentrations match up for each set-up and output averaging depth at each monitoring location, with a high correlation value indicating that temporal variations have been captured well by the model.

$$R = \frac{\frac{1}{n}\sum_{i=1}^{n}\left(C_{O_i} - \overline{C_O}\right)\left(C_{M_i} - \overline{C_M}\right)}{\sigma_{C_O}\sigma_{C_M}}, \qquad -1\ to\ 1, +1\ is\ perfect$$

Where σ_{C_O} and σ_{C_M} are the standard deviation of the observation data and model data respectively and *i* and *n* are the individual and total number of timesteps where both observation and model data are available.

Normalised Mean Square Error

Normalised mean square error, *NMSE*, is a measure of the scatter between two datasets

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caused by both systematic and random errors. It compares how spread out the model results are from the observations. A set of results with a low *NMSE* will have values that fit within a similar range to the observations.

$$NMSE = \frac{\sum_{i=1}^{n} \left(C_{M_i} - C_{O_i}\right)^2}{n\bar{C}_M\bar{C}_O}, \qquad 0\ to\ \infty, 0\ is\ perfect$$

Coefficient of Variation

The coefficient of variation, c_v, is a standardised measure of variation in a dataset, allowing for comparisons between datasets of differing magnitudes, across our monitoring locations and events. We want similar c_v values for the monitoring data and the NAME output to indicate that the NAME set-up is capturing time varying effects similarly to reality, even if the exact timing is incorrect.

$$c_v = \frac{\sigma}{\bar{C}}, \qquad where\ \sigma = \sqrt{\frac{\sum_{i=1}^{n}(C_i - \bar{C})^2}{n}}$$

Periodic Peak Time Difference

A measure to compare the timing of peak concentrations throughout the observation period. It is used in addition to correlation to overcome potential discrepancies in relative peak magnitudes caused by using a constant model release rate when the real release rate likely varies with time. For example, peaks at later observation times may appear to have greater significance in the model values than the observations if the real release rate was decreasing with time. By comparing the timing of concentration peaks over 12-hour day/night periods, a better understanding of the model fit can be made.

$$PPTD = \frac{\sum_{i=1}^{n} \frac{1}{length\ of\ period_i}\left(t\left(C_{M_{max\ in\ period_i}}\right) - t\left(C_{O_{max\ in\ period_i}}\right)\right)}{n},$$

$$-1\ to\ 1, 0\ is\ perfect$$

Where $t(C_{max})$ is the time where the maximum concentration in the period occurs and here *i* and *n* are the individual and total number of 12-hour periods available for both the observation and model data at the monitoring location.

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4. Results

We choose to analyse the events that occurred in Swansea and Swindon in greater detail due to their differing fire types and similar sized monitoring datasets. The equivalent set-up and output averaging depth rankings for Kidderminster, Smethwick and Sunderland are summarised in the Appendix, along with details on the contributing values, (Appendix Tables A3, A4 and A5) and all five case-studies contribute to the overarching results.

4.1. Swansea

Figure 2 presents the observed and modelled timeseries' of PM_{10} air concentrations for 18/06/2011 – 20/06/2011 at four of the Swansea monitoring locations (the full set of timeseries data can be seen in Appendix Figures A1 and A2).The modelled air concentrations broadly follow the same trends as the observations, although there are some missing and erroneous peaks noticeable in the modelled timeseries' for Broughton Avenue and Carmarthen Road. Comparing the forecast plume location between 01:00 – 02:00 UTC on 19 June 2011 (Figure 3) to the PM_{10} air concentrations at the monitoring locations in Figure 2 over the same period shows general agreement, with Broughton Avenue having the lowest observed and modelled concentrations and lying outside the expected plume location, Carmarthen Road showing elevated concentrations as the nearest monitoring location to the source within the plume and both Pentregethin Road and Rosecross House experiencing similar dips in concentration as they sit at the edge of the plume. The decreases, and subsequent increases, in PM_{10} air concentrations at Pentregethin Road and Rosecross House, due to changes in the wind conditions briefly dispersing the plume away from the two monitoring locations, are not as pronounced in the model output as in the observations, however, and the relative magnitudes of the modelled air concentrations at the two locations are more alike than observed, with the Carmarthen Road modelled air concentrations appearing higher in magnitude instead.

During the overnight period on the 19th (Figure 3), there is little noticeable difference between the 'default', 'near-source' and 'urban' simulations across any of the output averaging depths, but when the plume-rise scheme is used it is apparent that the simulated plume is transported higher in the atmosphere as greater air concentrations are visible at increasing depths. There is a very small difference in the plume shape produced by the 'plume-rise' and 'all' set-ups, with the 'all' set-up showing slightly greater downwind dispersion over 100 m. Later, between 18:00 – 19:00 UTC on 27 June 2011 (Figure 4), when winds are transitioning from southerlies to northerlies, more differences between the set-ups are visible, with PM_{10} being dispersed farther over Swansea Bay by the 'default' simulation than the other simulations and greater variations in the general shape of the plume seen with the set-ups using the plume-rise scheme. The 'near-source' and 'urban' simulations are still difficult to distinguish from one another however.

Returning to the timeseries output (Figure 2), we can see how the similarities between set-ups translate temporally. The relative magnitudes of the 'default', 'near-source' and 'urban'

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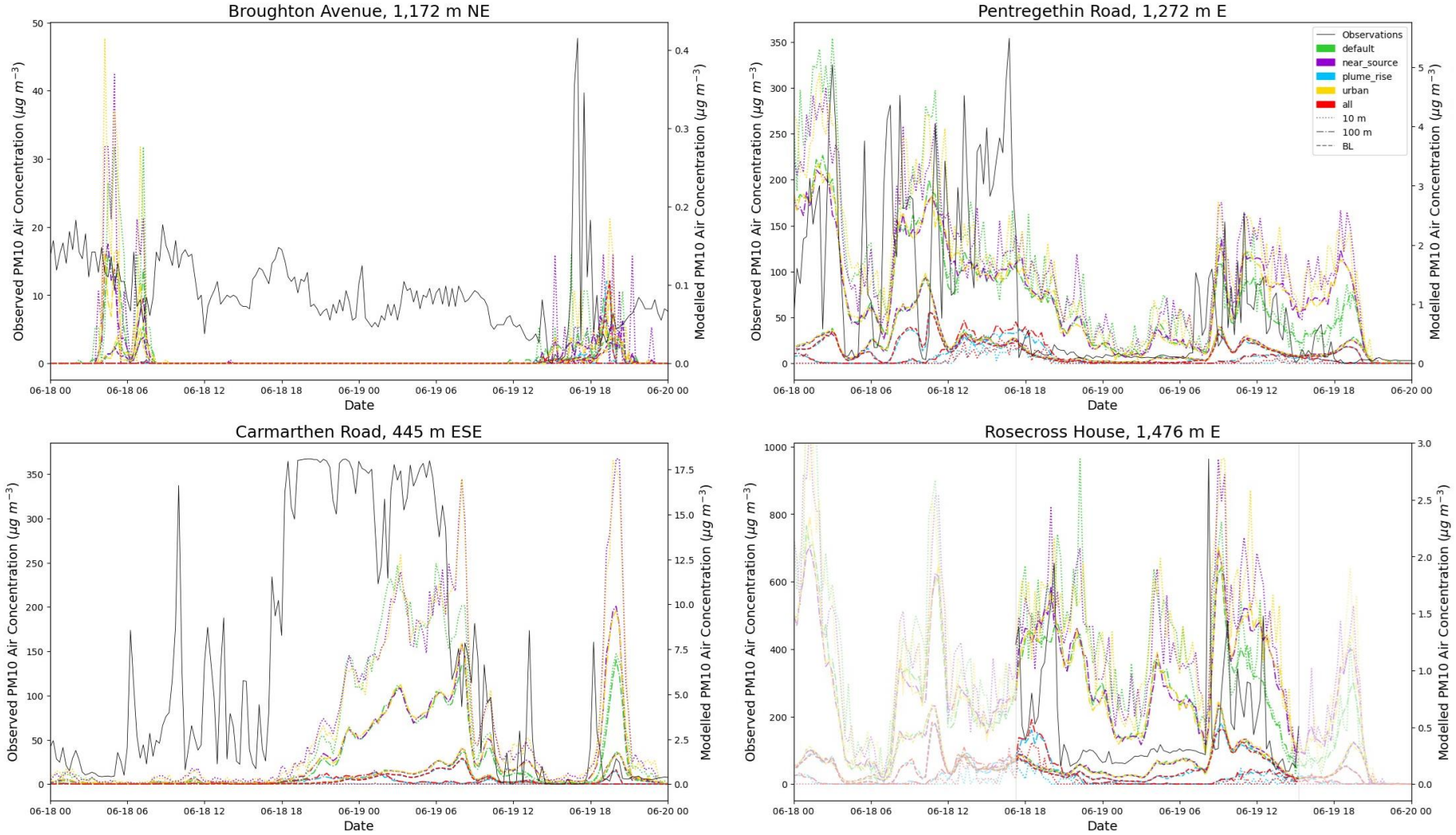

Figure 2: Timeseries plots showing the observed PM_{10} air concentrations and the non-scaled modelled air concentrations from 18/06/2011 – 20/06/2011 for four of the monitoring locations from the Swansea event. Faded areas on the Rosecross House plot indicate periods when no observations were made. Title text denotes downwind distance from the source.

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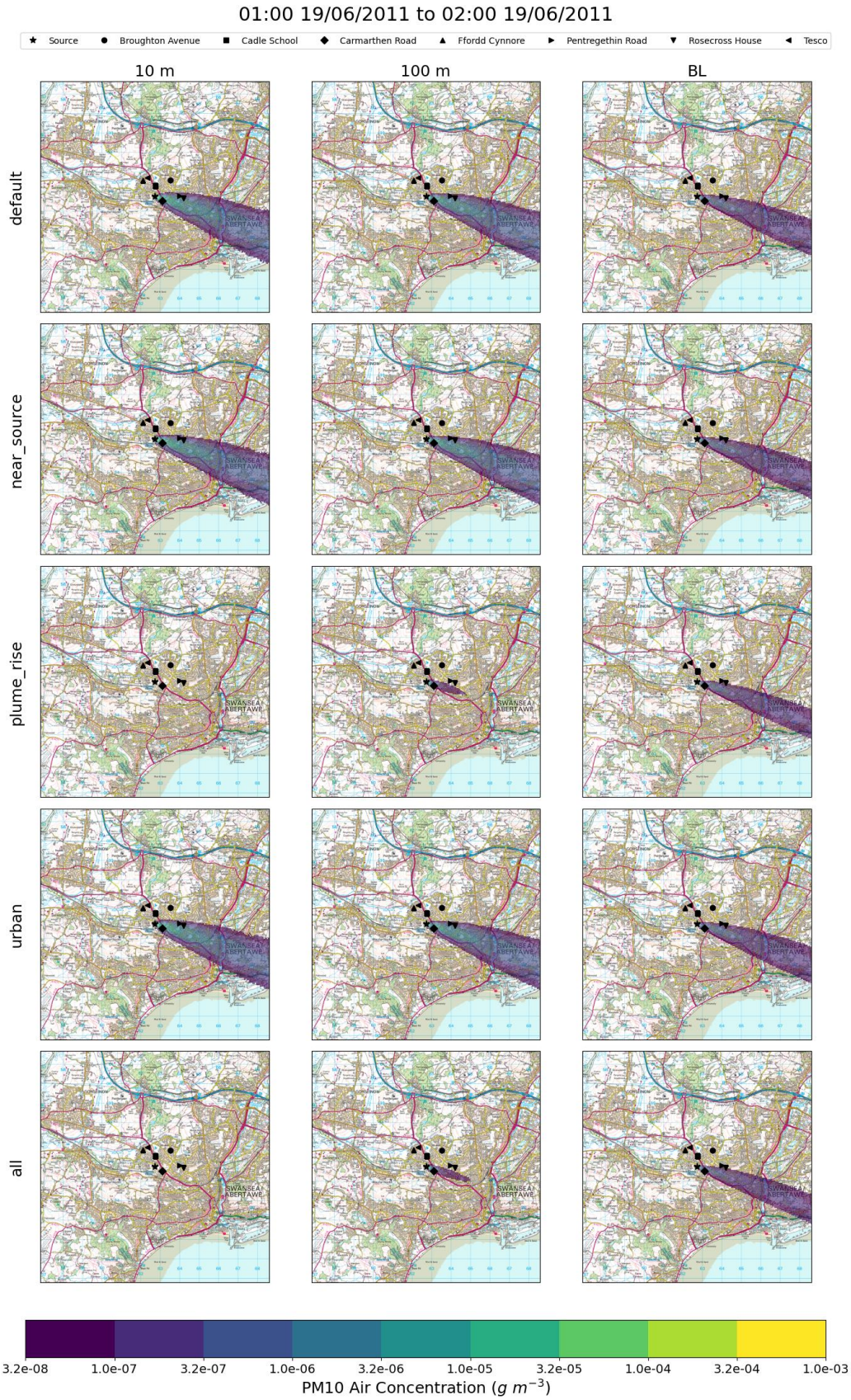

Figure 3: NAME dispersal plumes of the Swansea event showing the hourly average air concentration of PM_{10} between 01:00 – 02:00 19/06/2011 from each of the set-ups, using the three output averaging depths.
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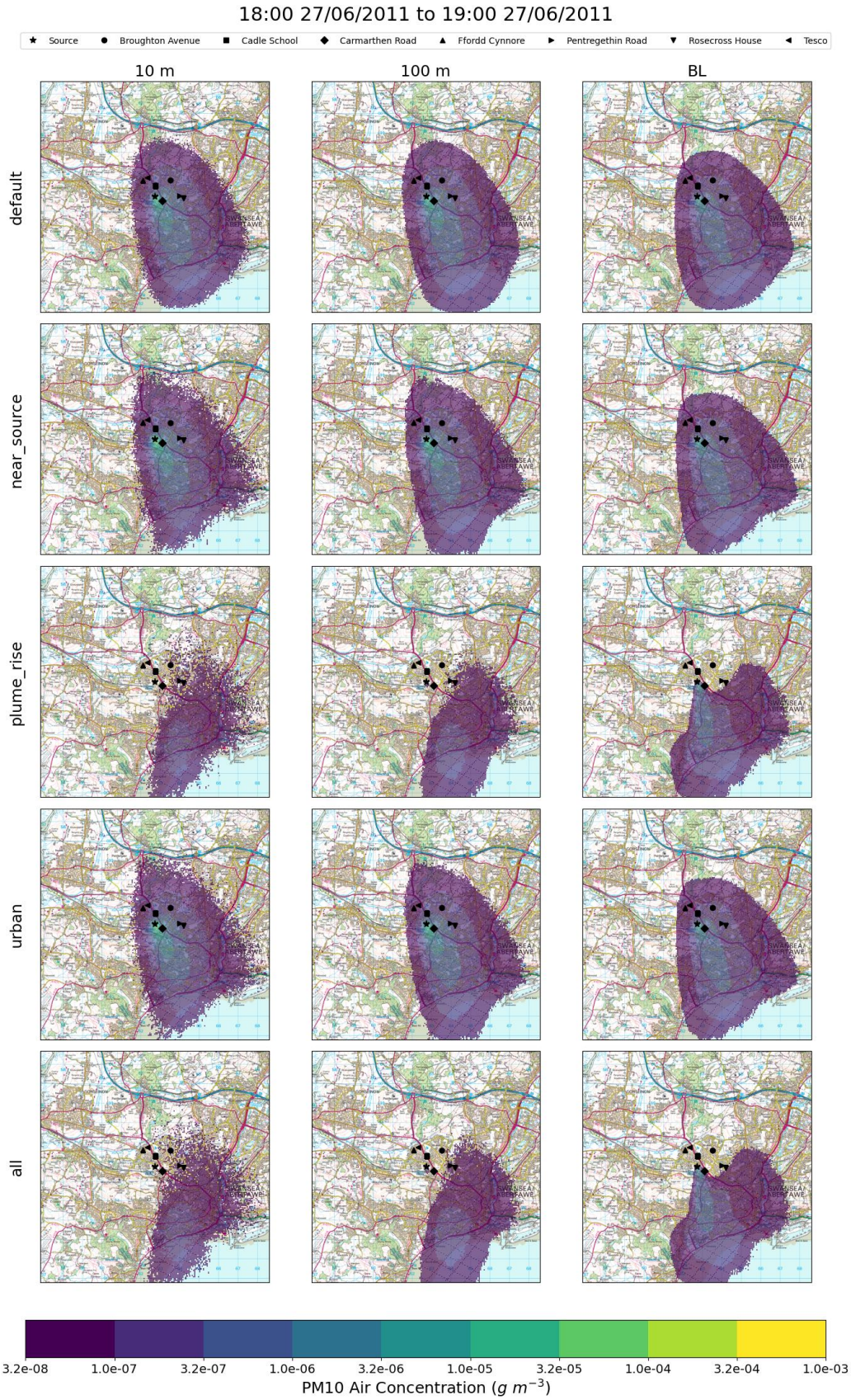

Figure 4: As for Figure 3 but between 18:00 – 19:00 27/06/2011.
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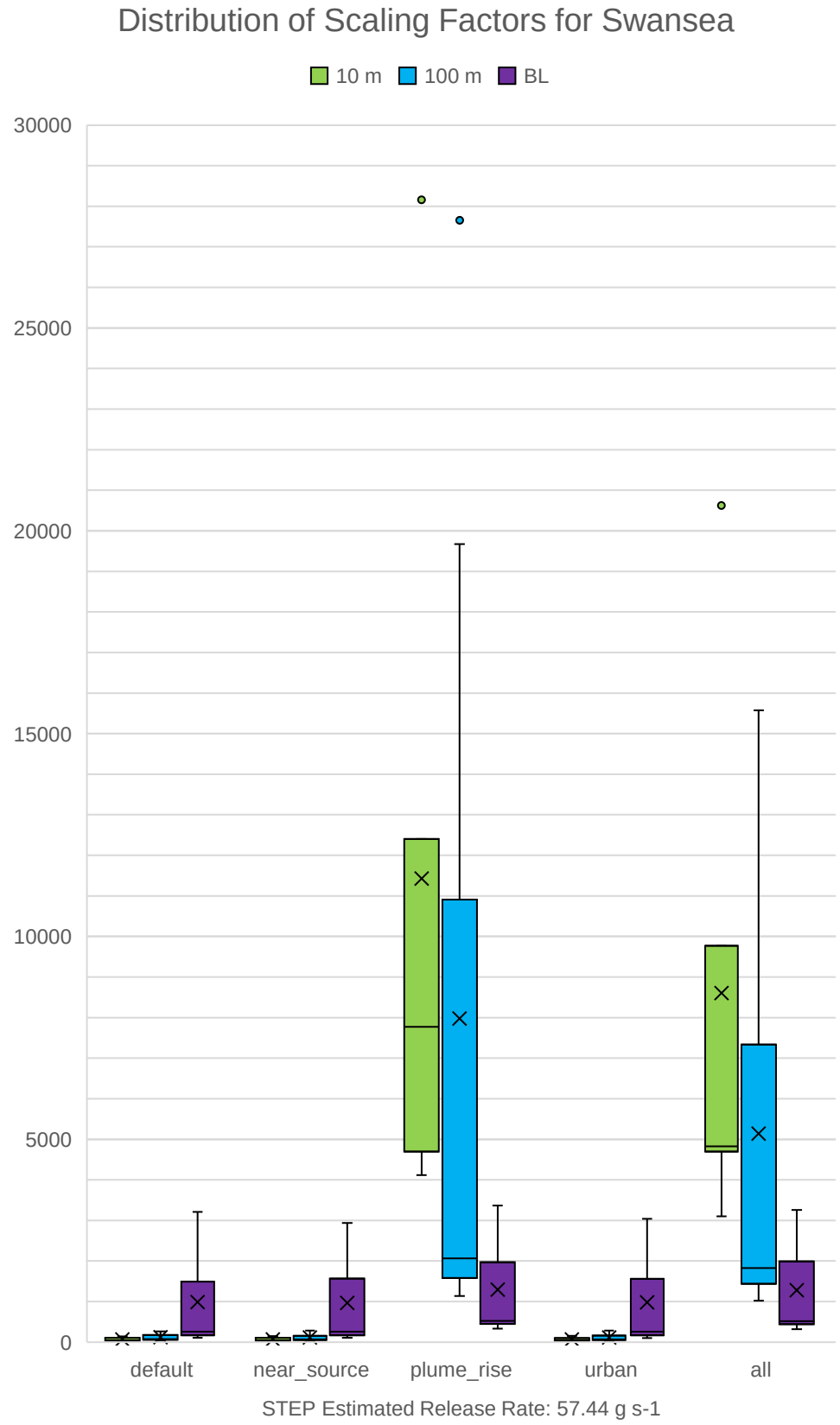

Figure 5: Box and whisker plot showing the distribution of the scaling factors calculated for the model output across all of the monitoring locations for the Swansea event. Boxes show the interquartile range (IQR), median and mean (cross), while the whiskers indicate the largest (smallest) scaling factor within 1.5 times the IQR of the third (first) quartile, with any values greater (smaller) than this marked as outliers.

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output are very similar across the three averaging depths, but differences in the size and timing of peak air concentrations are now more apparent. The relative magnitudes of the modelled air concentrations when using the 'plume-rise' and 'all' set-ups are smaller compared to the other set-ups, except for the BL averaged outputs which are of similar magnitudes to their counterpart outputs. Amongst the set-ups that do not use the plume-rise scheme, the 10 m averaged output has the largest concentration values with the BL averaged values being smallest. The opposite, however, is generally true for the set-ups that use the plume-rise scheme, with only brief periods of higher 100 m averaged output observed at Pentregethin Road and Rosecross House on the 18th. An analogous pattern can be seen in the distribution of scaling factors required to match the scale of the observation data at each site (Figure 5), with similar factors needed for the BL averaged output from each simulation, but increasingly smaller scaling factors required for decreasing output averaging depths, except for plume-rise simulations which require larger scaling factors with decreasing averaging depth and show greater variability in magnitude. When comparing the calculated scaling factors for each set-up and output averaging depth combination to the STEP estimated release rate for this event (57.44 g s^{-1}), it can be seen that scaling factors which are of the same order of magnitude as the STEP estimated release rate, across any of the output averaging depths, were only calculated for set-ups not using plume-rise scheme.

To assess the ability of each model set-up and output averaging depth option to match observations, we have ranked both the individual output averaging depths for each set-up and the joint set-up and output averaging depth combinations using their ability to produce the 'best' values for each statistical method. We collate the results for each monitoring station and determine which modelling options consistently produce optimal PM_{10} concentration estimates according to the statistical measures. The individual statistical values and the resultant rankings for Broughton Avenue are provided in Table 3 and Table 4, and we see that a 'near-source' simulation averaging air concentrations over 100 m is likely the 'best' choice for this location. This result is not consistent across each of the monitoring datasets for the event with, for example, the BL averaged 'plume-rise' output better fitting the PM_{10} monitoring data at Pentregethin Road (Appendix Tables A1 and A2). To determine the 'best' model set-up across the entire observation dataset, the results for all the monitoring locations are tallied to produce a ranking of all the combinations for the event (Table 5). From this we see that using the 'near-source' or 'urban' set-ups and averaging air concentrations over 100 m is likely to better match our observation data for this event, while running with the plume-rise scheme and averaging air concentrations over shallower depths is unlikely to. We note that across the entire event (Table 5) and for individual monitoring locations (Table 4, Appendix Table A2), the highest ranked output averaging depth for a particular set-up is not always the better performing output averaging depth combination when compared to all the other combinations. For example, when looking at the 'all' set-up in isolation, using a BL output averaging depth looks to be the 'best' option for the Swansea event, but when compared with the other set-up combinations using a 100 m output averaging depth with the 'all' set-up performs better.

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Table 3: Summary statistics for the Broughton Avenue monitoring location from the Swansea event. Green highlights indicate the 'best' value for a statistic for the corresponding set-up, which contributes to the set-up count of 'best' output averaging depth. Blue highlights indicate the same as green highlights and additionally that the value is the 'best' across all the set-up and output averaging depth combinations, thus contributing to the 'best' set-up and output averaging depth combination count.

Broughton Avenue Statistics

Set-up	Depth	R	NMSE	Δc_V	PPTD
Default	**10 m**	0.28	9.41	0.51	-0.12
	100 m	0.34	7.45	0.18	-0.14
	BL	0.26	8.75	0.27	-0.12
Near-Source	**10 m**	0.35	7.59	0.24	-0.15
	100 m	0.37	7.00	0.14	-0.15
	BL	0.27	8.53	0.24	-0.16
Plume-Rise	**10 m**	0.11	44.02	4.19	-0.39
	100 m	0.22	16.18	1.57	-0.29
	BL	0.30	8.90	0.44	-0.21
Urban	**10 m**	0.35	7.49	0.21	-0.13
	100 m	0.36	7.01	0.13	-0.14
	BL	0.26	8.61	0.25	-0.12
All	**10 m**	0.09	42.16	4.00	-0.37
	100 m	0.21	16.92	1.66	-0.27
	BL	0.30	9.02	0.46	-0.20

Table 4: Ranked output averaging depths for each set-up and ranked set-up and output averaging depth combinations for the Broughton Avenue monitoring location from the Swansea event, using the 'best' statistic counts from Table 3.

Broughton Avenue Rankings

Set-up	Depth	Total # statistics with 'best' value for set-up
Default	**100 m**	3
	10 m	1
	BL	1
Near-Source	**100 m**	4
	10 m	0
	BL	0
Plume-Rise	**BL**	4
	10 m	0
	100 m	0
Urban	**100 m**	3
	BL	1
	10 m	0
All	**BL**	4
	10 m	0
	100 m	0

Set-up and Depth Combination	Total # statistics with 'best' value
near_source_100 m	2
urban_100 m	1
urban_BL	1
all_10 m	0
all_100 m	0
all_BL	0
default_10 m	0
default_100 m	0
default_BL	0
near_source_10 m	0
near_source_BL	0
plume_rise_10 m	0
plume_rise_100 m	0
plume_rise_BL	0
urban_10 m	0

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Table 5: Ranked output averaging depths for each set-up and ranked set-up and output averaging depth combinations using the 'best' statistic counts from all monitoring locations for the Swansea event.

Swansea Rankings

Set-up	Depth	Total # statistics with 'best' value for set-up
Default	100 m	20
	BL	7
	10 m	4
Near-Source	100 m	20
	BL	7
	10 m	5
Plume-Rise	BL	25
	100 m	4
	10 m	1
Urban	100 m	16
	10 m	6
	BL	6
All	BL	23
	100 m	5
	10 m	0

Set-up and Depth Combination	Total # statistics with 'best' value
near_source_100 m	8
urban_100 m	6
near_source_10 m	4
plume_rise_BL	4
urban_10 m	3
all_100 m	2
default_100 m	2
near_source_BL	2
urban_BL	2
all_BL	1
default_10 m	1
default_BL	1
plume_rise_10 m	1
all_10 m	0
plume_rise_100 m	0

4.2. Swindon

For Swindon, we start by looking at the gridded output from 02:00 – 03:00 UTC on 28 August 2014 (Figure 6) and see that again the set-ups that use the plume-rise scheme produce the most different plumes, with the PM_{10} particles being dispersed further east. Comparing the 'default' plumes and the 'near-source' and 'urban' plumes we can see that the 3.2 – 10 $x10^{-7}$ g m^{-3} contour does not extend as far downwind in the runs using the near-source scheme at all depths. Around this time in the timeseries data (Figure 7), we see PM_{10} air concentrations start to increase at the locations to the east of the source in both the observations and model output. While the concentrations start to increase at a similar time in all the simulations, the peaks appear to diminish earlier in the simulations using the plume-rise scheme at Colebrook Road and Homebase. The behaviour throughout the rest of the day is similar between most of the set-ups at these two locations, although later simulated peaks occur at differing relative magnitudes than observed. Nuffield Health had monitoring data from two sets of equipment, and we see near-identical variations detected by both, with only slight differences in magnitude, but unfortunately our model output only partially captures the general increasing trend, instead predicting higher air concentrations at earlier times as well as later. Across all the monitoring locations, we can see that the relative magnitudes of the NAME air concentrations follow the same pattern as the Swansea case-study, with the plume-rise simulations producing larger air concentrations with increasing averaging depth, while the other simulations' magnitudes decrease in size with increasing averaging depth. Unlike Swansea, the relative scale of the model air concentrations between each site match those of the observations in this case study.

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Figure 6: NAME dispersal plumes of the Swindon event showing the hourly average air concentration of PM_{10} between 02:00 – 03:00 28/08/2014 from each of the set-ups, using the three output averaging depths.
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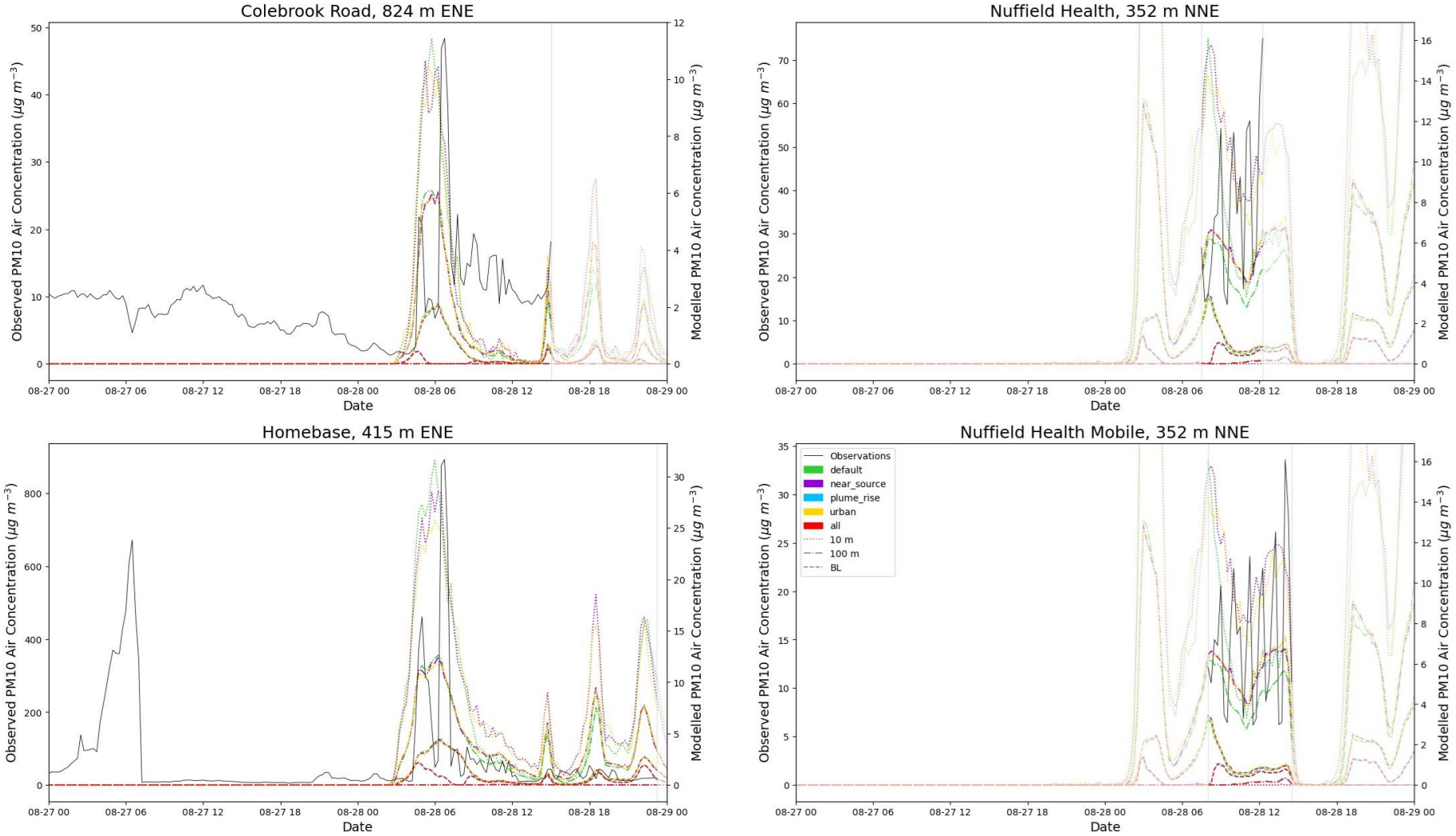

Figure 7: Timeseries plots showing the observed PM_{10} air concentrations and the non-scaled modelled air concentrations from 27/06/2014 – 29/06/2014 for three of the monitoring locations from the Swindon event, with an extra plot for the additional mobile monitoring at the Nuffield Health location. Faded areas on the Colebrook Road and both Nuffield Health plots indicate periods when no observations were made. Title text denotes downwind distance from the source.

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Table 6: Ranked output averaging depths for each set-up and ranked set-up and output averaging depth combinations using the 'best' statistic counts from all monitoring locations for the Swindon event.

Swindon Rankings

Set-up	Depth	Total # statistics with 'best' value for set-up
Default	10 m	11
	100 m	10
	BL	3
Near-Source	100 m	15
	BL	10
	10 m	4
Plume-Rise	BL	14
	100 m	10
	10 m	0
Urban	100 m	11
	BL	8
	10 m	5
All	BL	14
	100 m	10
	10 m	0

Set-up and Depth Combination	Total # statistics with 'best' value
all_100 m	8
urban_100 m	6
plume_rise_100 m	5
near_source_BL	3
all_BL	2
default_10 m	2
default_BL	1
near_source_100 m	1
plume_rise_BL	1
urban_BL	1
all_10 m	0
default_100 m	0
near_source_10 m	0
plume_rise_10 m	0
urban_10 m	0

To better understand how well the model air concentrations match the observations we look to the set-up rankings for this event (Table 6). Averaging air concentrations over a 100 m depth when not using the plume-rise scheme and over the BL when using it are again seen to be the 'best' options for the individual set-ups, although using a 10 m averaging depth with the 'default' set-up performs similarly against the observations from this event as well. When it comes to the set-up and output averaging depth combinations that most often provide the 'best' statistics overall, we find that while averaging 'urban' output over 100 m still matches observations well, using this depth with the 'all' or 'plume-rise' set-ups also rank highly for this event. Using a 10 m averaging depth with any set-up is then least likely to match the observations for Swindon.

4.3. Overall

For most set-ups the overall magnitude of the air concentrations decreases with increasing averaging depth, but for the set-ups using the plume-rise scheme the opposite trend is apparent most of the time. Both the Swansea (Figure 2) and Sunderland (not shown) events exhibit notable periods where this pattern is broken at some of their monitoring locations, with a 100 m output averaging depth used for the 'all' and 'plume-rise' set-ups sometimes producing larger air concentrations than with the BL output averaging depth. The scaling factors calculated to compare to the observations show the opposite behaviour, with larger scaling factors needed to balance smaller modelled air concentrations. When applied to the modelled unit release rate, the resultant scaled release rates can be compared to the STEP estimated emission rates in Figure 8. These results show that the set-up and output

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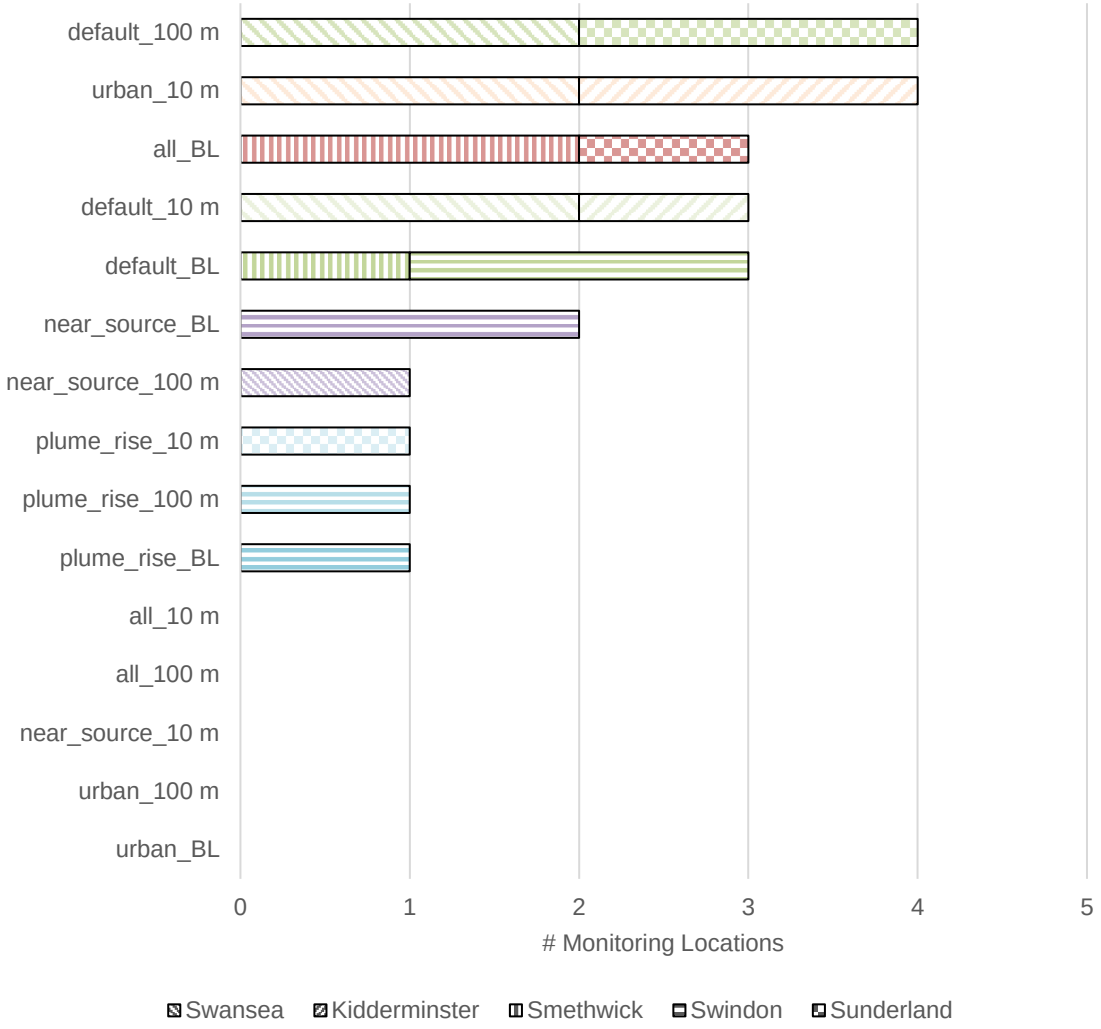

Figure 8: Set-up and output averaging depth combinations across all case-study events ranked based on scaled emission rate closeness to STEP estimated emission rates for each monitoring location. The contributing events are indicated by the shading patterns.

averaging depth combinations that manage to best match the scale of the STEP estimated emission rates while also matching the magnitude of the observations are most often the 'default' set-up with any of the three output averaging depths. Interestingly, the 'plume-rise' and 'all' set-ups, which also use the STEP estimated release temperature and flow velocity, do not often produce scaled release rates that well match the STEP estimated release rates.

The suitability of each output averaging depth for each set-up can be seen in Figure 9, where the options are ranked by total count of 'best' statistic values with the contributing statistic counts detailed as well. As discovered for Swansea and Swindon, 'default', 'near-source' and 'urban' perform better against the observations when air concentration outputs are taken as an average over 100 m, while 'plume-rise' and 'all' air concentration outputs fit the observations better when averaged over the BL. Using a 10 m output averaging depth with any of the set-ups rarely produced the 'best' statistical results. The influence of the four analysis statistics appears to be fairly even for the top ranked output averaging depths, with no one statistic dictating the results.

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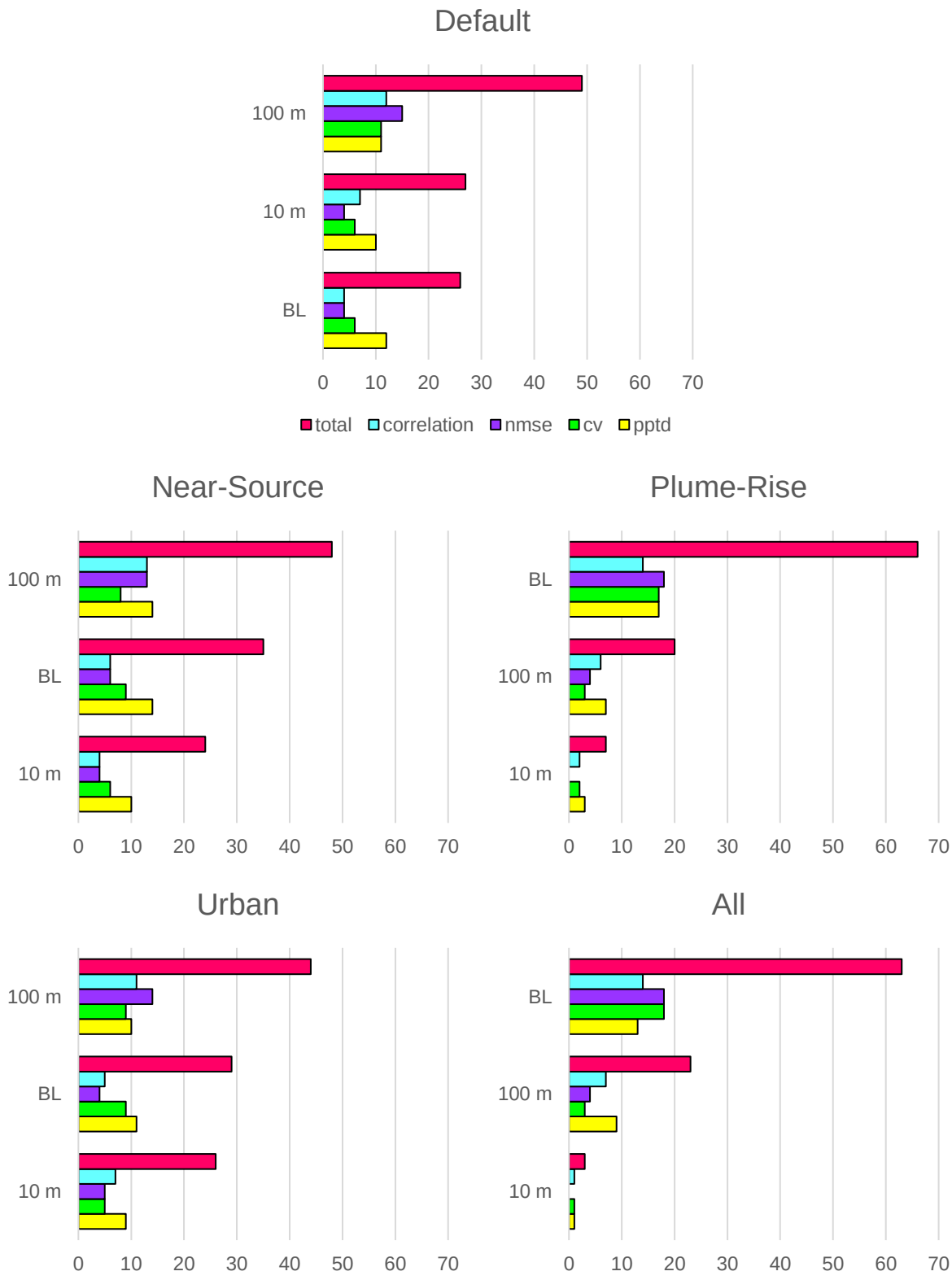

Figure 9: Sorted total 'best' statistic counts and contributing 'best' statistic counts for each statistic from all case-study events for the output averaging depth options for each set-up.

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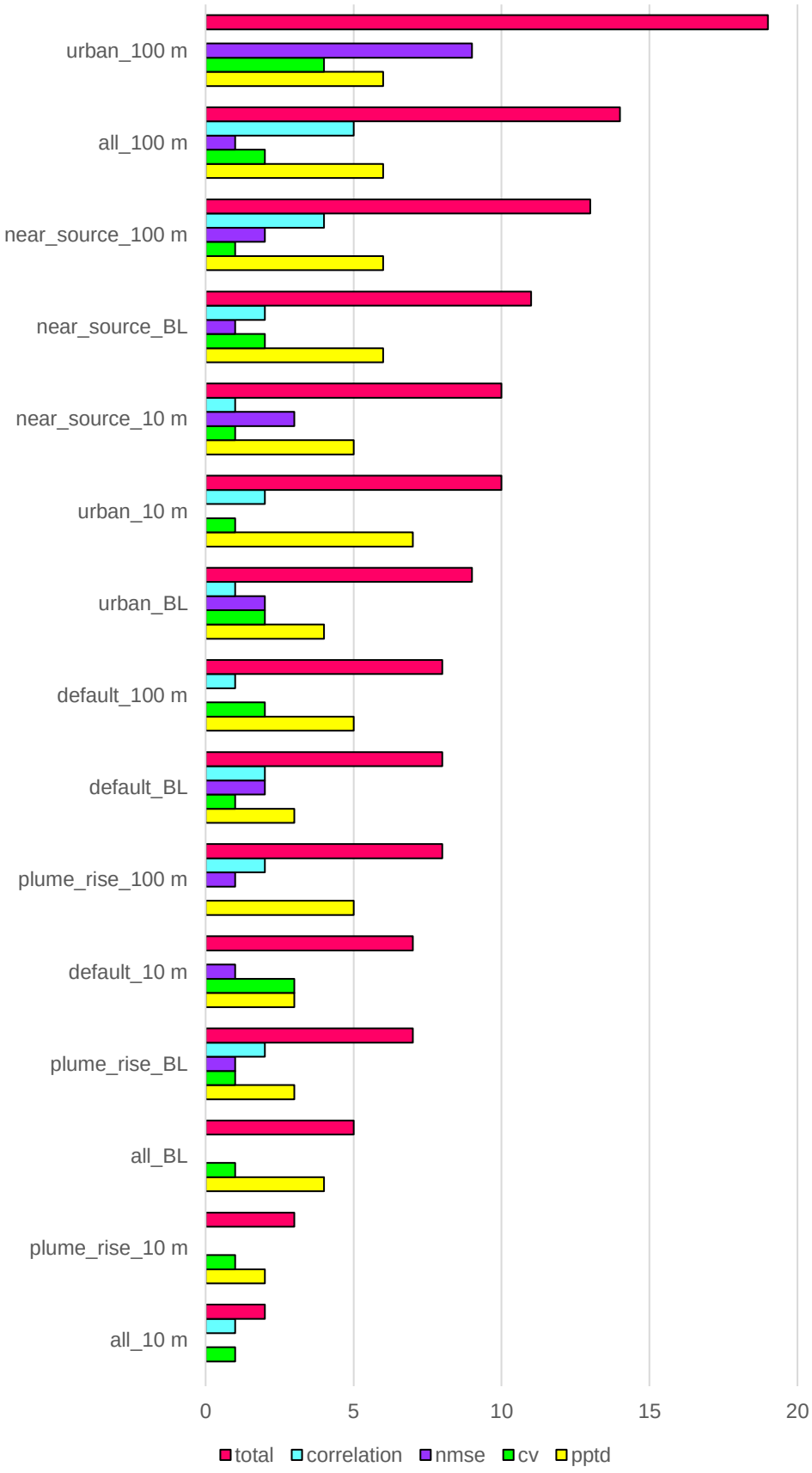

Figure 10: Sorted total 'best' statistic counts and contributing 'best' statistic counts for each statistic from all case-study events for the set-up and output averaging depth combinations.

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Looking across the entire set-up and output averaging depth combination spectrum (Figure 10), we find that using the ‘urban’ set-up and averaging PM_{10} air concentrations over a 100 m depth performs better than the other set-ups most often. This combination does not routinely perform ‘best’ in terms of *correlation* however, with the rank position being mostly influenced by the statistics that indicate whether the model correctly matches the amount and scale of variation in the observations, *NMSE* and c_v, but not necessarily the timing. The next highest ranked set-up combinations are ‘all’ and ‘near-source’ again averaging over a 100 m depth. Conversely to the top rank, these two are more heavily influenced by the overall *correlation* of model output to observations and the temporal matching of peak air concentrations (*PPTD*) than the ability to capture the variability similarly. The ‘all’ set-up performing better overall when using a 100 m output averaging depth over a BL output averaging depth as suggested when looking at the set-up individually (Figure 9) is mirrored in the ‘plume-rise’ results as well, although the 10 m option for both remains in last place across all the set-up and output averaging depth combinations.

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5. Discussion

In this study, we have considered the use of three sophisticated physics schemes for modelling the short-range transport and dispersion of pollutants from industrial fires. We evaluated model simulations against point observations of PM_{10} at the surface from five case studies, studying both the predicted location and extent of the plumes and the concentrations of the pollutant. We have shown that when designing the optimal model set-up the choice of schemes must be considered in combination with the choice of output averaging depth. Our statistical comparisons to observed PM_{10} concentrations at point locations suggest that the 'urban, 'all' and 'near-source' set-ups using a 100 m output averaging depth perform better than the simpler 'default' set-up using a 100 m output averaging depth, however the hourly-averaged plume dispersal plots produced using the 'default', 'near-source' and 'urban' set-ups show predicted extents that look very similar. Given CHEMETs include plume dispersal plots, the impact of using the 'near-source' or 'urban' schemes to produce this style of product should be considered further.

Although using the urban scheme in the 'urban' and 'all' set-ups produced statistically better air concentration estimates compared to the observations than the set-ups in which it was not used ('near-source' and 'plume-rise'), it had little impact on the simulated location and extent of the plumes. It is noted that while the UKV urban fractions surrounding our event locations are higher than the activation threshold for the scheme, they are relatively low. Further work exploring the sensitivity of different NAME simulation output to the input urban fractions would be a useful next step to understanding the scheme's potential usefulness in operational set-ups.

Using the plume-rise scheme has a significant impact on the predicted plume extent and location along with the predicted near-surface air concentrations. This is likely due to the scheme lofting model particles to higher altitudes, allowing them to potentially encounter different meteorological conditions and moving them away from the lower two output averaging depths, thereby reducing the near-surface concentrations. This behaviour will have influenced our results for the 'plume-rise' and 'all' set-ups because if there are no significant air concentrations at lower depths then the BL output averaging depth will have performed 'best' automatically. Previous studies have shown that the plume-rise scheme demonstrates skill in representing the influence of the diurnal variation and mixing within the boundary layer (Kendall et al. 2019a, 2019b.). However, it has also been shown to consistently underestimate the depth of plumes and may therefore lack the ability to accurately represent near-surface air concentrations of pollutants (Webster et al. 2006., 2011). Before conclusions can be dawn on the effectiveness of using the plume-rise scheme to generate plume simulations for CHEMETs, more work is needed to confirm whether the STEP estimated source terms are optimal for representing our case-studies with the plume-rise scheme and to evaluate whether the scheme is placing pollutants at the correct height in the atmosphere.

To accurately predict downwind concentrations of a pollutant, the source emission rate must be known. We have shown that using STEP to estimate emission rates produced values of

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suitable magnitude to match observations when using some of the model set-up and output averaging depth combinations. However, the combinations that produced scaled release rates that best matched the scale of the STEP output were not the ‘best’ performing set-up and output averaging depth combinations statistically. Even disregarding this mismatch, there are further challenges to using STEP release rates operationally, namely the requirement to have knowledge of the fire type, size, duration and total flammable load to run STEP, which is likely to be difficult to obtain in real-time during an emergency response event.

We assessed the performance of the NAME simulations using multiple statistical techniques. To draw conclusions on the optimal set-up and output averaging depth combination we ranked them using the ‘best’ results of the statistical analysis. In ranking the set-up and output averaging depth combinations for the individual case-studies, we saw some variation in which set-ups ranked first for each event, but once combined a clearer outcome came together. Our focus on the single ‘best’ result for each statistic at each monitoring location could be undervaluing set-up and output averaging depth combinations that perform highly but never rank first for any statistics in certain events. A different approach could help overcome this oversight.

It should be recognised that there are underlying uncertainties in both the observations, including the influence of background pollutant contributions, and NWP data that have not been accounted for here, which will affect the timings and magnitude of the measured and modelled peak concentrations. Furthermore, the sparse and sporadic network of observations for each of the events makes it difficult to comment on the accuracy of the predicted location and extent of the plumes for these case-studies.

Finally, we should acknowledge that using any of the schemes is known to add computational run time to NAME simulations and for the case-studies explored here it was seen that using the urban scheme made the NAME runs the slowest, by up to a factor of three compared to the default set-up (Appendix Figure A3). However, the length of simulations for our events was many days longer than a typical CHEMET forecast would be, with additional output not ordinarily required for a CHEMET, meaning that the impact over a shorter modelling period with only CHEMET output could vary and should be investigated.

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6. Conclusions

In our investigation to see whether plume dispersal modelling for fire related emergency response operations could be improved by utilising short-range dispersion schemes in NAME, the following conclusions have been reached and suggested next steps proposed:

- Our current operational set-up produced the 'best' matching output to ground-level observations of PM_{10} when using a 100 m output averaging depth, as is used currently.
- When considering the use of additional schemes, using the urban scheme, which is reliant on the near-source scheme, and producing model output over a 100 m depth has been found to best represent the observed air concentrations of PM_{10} most often throughout our case-studies. Using the near-source scheme with a 100 m output averaging depth on its own was also found to match observations well. The plume dispersal plots produced by both set-ups look similar to those produced by the operational set-up, however, so the impact on this output type should be investigated to determine if the changes are significant enough to warrant changing the set-up for the operational CHEMET plume forecasts. Another factor to be considered is whether introducing either scheme to the CHEMET set-up would detrimentally increase the model run-times to the point of impacting operational response times.
- The plume-rise scheme, initiated using STEP and reliant on the near-source scheme, has the potential to represent the buoyant dispersal of emissions from waste fires when used together with the urban scheme, as demonstrated by the 'all' set-up, but the inconsistency in the ability for this set-up to produce usable output over 100 m depths is currently a hinderance to implementing it operationally. The plume-rise scheme and the contributing role of STEP should therefore be investigated further to work out the viability of their use during emergency response for fire events. Given the plume-rise scheme and STEP both require additional information that is difficult to acquire during or after an event this would also need to be considered as part of any decision-making process to utilise them as part of our CHEMET process in the future.
- STEP was shown to produce emission rate estimates of suitable magnitudes to match observations when used with model output from set-ups not using the plume-rise scheme so there is potential for it to be used in this context too. It would be good to gain a better understanding of STEP from HSE and EA while investigating this.
- The improvements seen from using any of the additional schemes are not guaranteed to follow through to the current operational products, but their use during post-event investigations once more information is available, such as those performed here, could be beneficial.

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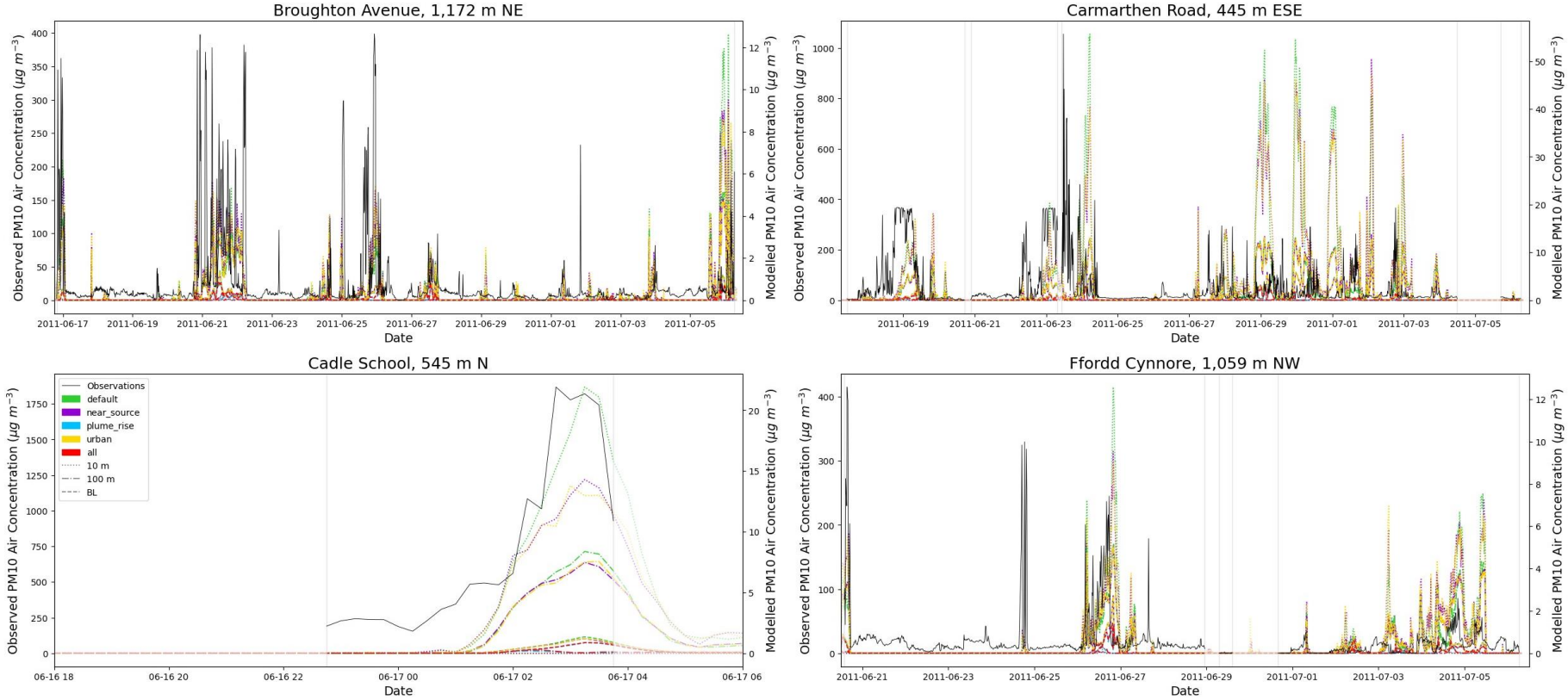
Appendix

Additional figures and tables displaying the results from modelling the plume dispersal from waste fire events using five NAME set-ups: the ‘default’ set-up based on the operational CHEMET set-up, the ‘near-source’ set-up using the near-source scheme, the ‘plume-rise’ set-up using the near-source and plume-rise schemes, the ‘urban’ set-up using the near-source and urban schemes, and the ‘all’ set-up using the near-source, urban and plume-rise schemes.



Appendix Figure A1: Complete timeseries plots showing the observed PM_{10} air concentrations and the non-scaled modelled air concentrations for four of the monitoring locations from the Swansea event. Faded areas indicate periods when no observations were made. Title text denotes downwind distance from the source.

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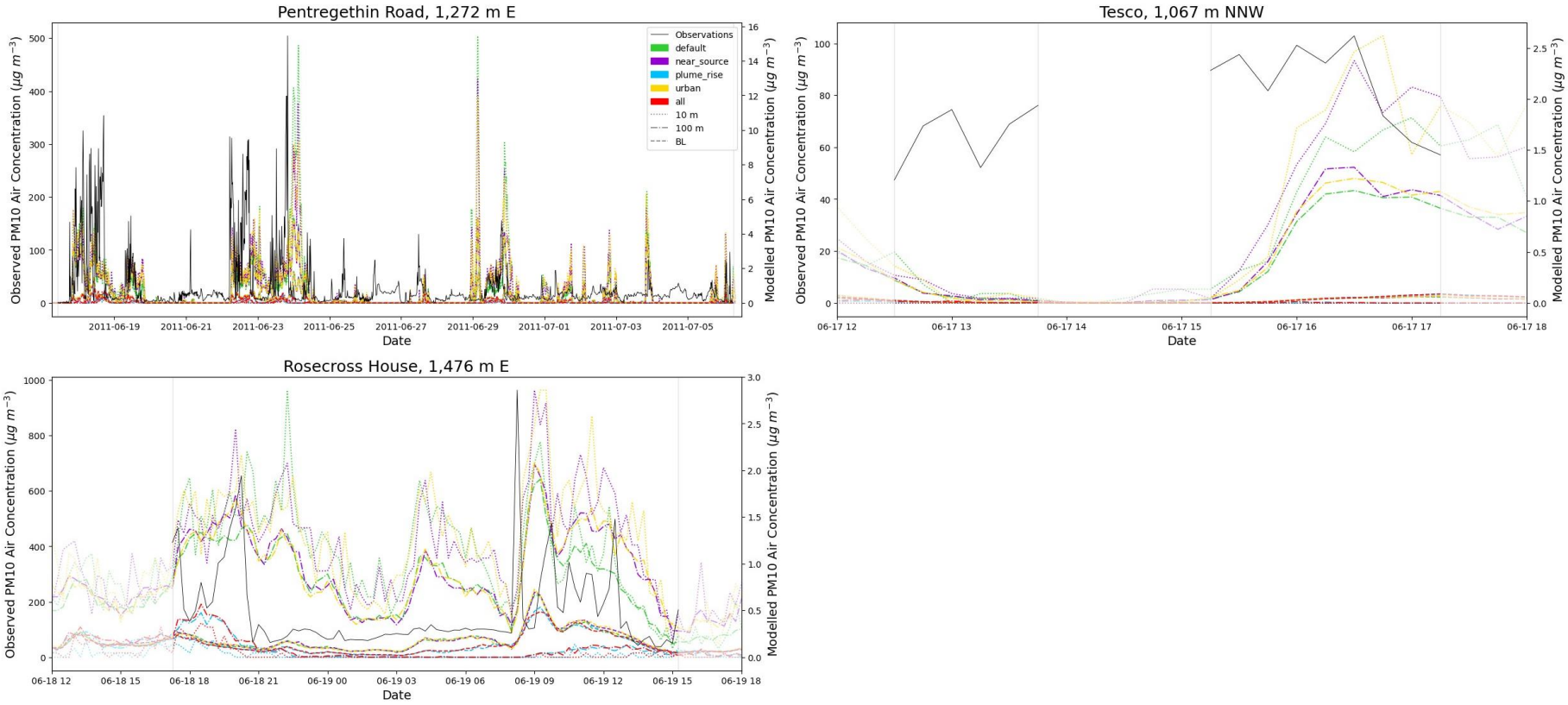

Appendix Figure A2: Complete timeseries plots showing the observed PM_{10} air concentrations and the non-scaled modelled air concentrations for three of the monitoring locations from the Swansea event. Faded areas indicate periods when no observations were made. Title text denotes downwind distance from the source.

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Appendix Table A1: Summary statistics for the Pentregethin Road monitoring location from the Swansea event. Green highlights indicate the 'best' value for a statistic for the corresponding set-up, which contributes to the set-up count of 'best' output averaging depth. Blue highlights indicate the same as green highlights and additionally that the value is the 'best' across all the set-up and output averaging depth combinations, thus contributing to the 'best' set-up and output averaging depth combination count.

Pentregethin Road Statistics

Set-up	Depth	R	NMSE	Δc_V	PPTD
Default	10 m	0.17	6.82	0.52	0.02
	100 m	0.37	3.95	0.04	0.01
	BL	0.22	5.83	0.36	-0.01
Near-Source	10 m	0.27	4.64	0.08	-0.01
	100 m	0.39	3.54	-0.07	-0.02
	BL	0.24	5.53	0.30	-0.00
Plume-Rise	10 m	0.34	19.53	2.95	-0.29
	100 m	0.50	6.76	1.25	-0.11
	BL	0.56	3.17	0.27	-0.06
Urban	10 m	0.27	4.59	0.06	-0.00
	100 m	0.40	3.49	-0.08	-0.05
	BL	0.24	5.51	0.29	-0.02
All	10 m	0.35	17.42	2.72	-0.24
	100 m	0.48	7.54	1.38	-0.18
	BL	0.55	3.23	0.29	-0.07

Appendix Table A2: Ranked output averaging depths for each set-up and ranked set-up and output averaging depth combinations for the Pentregethin Road monitoring location from the Swansea event, using the 'best' statistic counts from Appendix Table A1.

Pentregethin Road Rankings

Set-up	Depth	Total # statistics with 'best' value for set-up
Default	100 m	3
	BL	1
	10 m	0
Near-Source	100 m	3
	BL	1
	10 m	0
Plume-Rise	BL	4
	10 m	0
	100 m	0
Urban	10 m	2
	100 m	2
	BL	0
All	BL	4
	10 m	0
	100 m	0

Set-up and Depth Combination	Total # statistics with 'best' value
plume_rise_BL	2
default_100 m	1
urban_10 m	1
all_10 m	0
all_100 m	0
all_BL	0
default_10 m	0
default_BL	0
near_source_10 m	0
near_source_100 m	0
near_source_BL	0
plume_rise_10 m	0
plume_rise_100 m	0
urban_100 m	0
urban_BL	0

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Appendix Table A3: Ranked output averaging depths for each set-up and ranked set-up and output averaging depth combinations using the 'best' statistic counts from all monitoring locations for the Kidderminster event.

Kidderminster Rankings

Set-up	Depth	Total # statistics with 'best' value for set-up
Default	BL	7
	100 m	5
	10 m	1
Near-Source	BL	7
	100 m	5
	10 m	3
Plume-Rise	BL	8
	10 m	0
	100 m	0
Urban	BL	7
	100 m	5
	10 m	2
All	BL	7
	100 m	1
	10 m	0

Set-up and Depth Combination	Total # statistics with 'best' value
urban_BL	5
default_100 m	2
near_source_10 m	2
near_source_100 m	2
urban_100 m	2
all_100 m	1
default_10 m	1
default_BL	1
near_source_BL	1
plume_rise_BL	1
urban_10 m	1
all_10 m	0
all_BL	0
plume_rise_10 m	0
plume_rise_100 m	0

Appendix Table A4: Ranked output averaging depths for each set-up and ranked set-up and output averaging depth combinations using the 'best' statistic counts from all monitoring locations for the Smethwick event.

Smethwick Rankings

Set-up	Depth	Total # statistics with 'best' value for set-up
Default	100 m	7
	10 m	4
	BL	4
Near-Source	BL	5
	10 m	4
	100 m	4
Plume-Rise	BL	12
	10 m	0
	100 m	0
Urban	100 m	6
	BL	5
	10 m	4
All	BL	12
	10 m	0
	100 m	0

Set-up and Depth Combination	Total # statistics with 'best' value
default_BL	3
near_source_10 m	3
near_source_BL	3
urban_10 m	3
urban_100 m	3
default_10 m	2
default_100 m	2
near_source_100 m	1
all_10 m	0
all_100 m	0
all_BL	0
plume_rise_10 m	0
plume_rise_100 m	0
plume_rise_BL	0
urban_BL	0

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Appendix Table A5: Ranked output averaging depths for each set-up and ranked set-up and output averaging depth combinations using the 'best' statistic counts from all monitoring locations for the Sunderland event.

Sunderland Rankings

Set-up	Depth	Total # statistics with 'best' value for set-up
Default	10 m	7
	100 m	7
	BL	5
Near-Source	10 m	8
	BL	6
	100 m	4
Plume-Rise	BL	7
	10 m	6
	100 m	6
Urban	10 m	9
	100 m	6
	BL	3
All	100 m	7
	BL	7
	10 m	3

Set-up and Depth Combination	Total # statistics with 'best' value
all_100 m	3
plume_rise_100 m	3
urban_10 m	3
all_10 m	2
all_BL	2
default_100 m	2
default_BL	2
near_source_BL	2
plume_rise_10 m	2
urban_100 m	2
default_10 m	1
near_source_10 m	1
near_source_100 m	1
plume_rise_BL	1
urban_BL	1

A note on the contributing values to the ranking tables (Tables 5 and 6 and Appendix Tables A3, A4 and A5) and total sorted statistic counts displayed in Figures 9 and 10: For all statistics except PPTD there is only one 'best' value per observation location, so the total count of 'best' values should equal #statistics x #locations. However, no non-zero output was produced for Brasshouse from the Smethwick event so there is one location less for the Smethwick rankings (Appendix Table A4) and total counts (Figures 9 and 10) than expected. Furthermore, no non-zero model output was produced at Gould Avenue from the Kidderminster event for the 'plume-rise' or 'all' set-ups, reducing the number of contributing locations for the output averaging depth rankings for these set-ups at Kidderminster (Appendix Table A3) and reducing the total counts for the output averaging depths for these set-ups (Figure 9). Due to the method of determination for PPTD, it is possible for multiple set-up and output averaging depth combinations at a monitoring location to produce the same value, meaning there can be more than one contribution to the 'best' value counts from PPTD, as seen in Table 3, which can lead to the total count for a particular table or figure being greater than expected.

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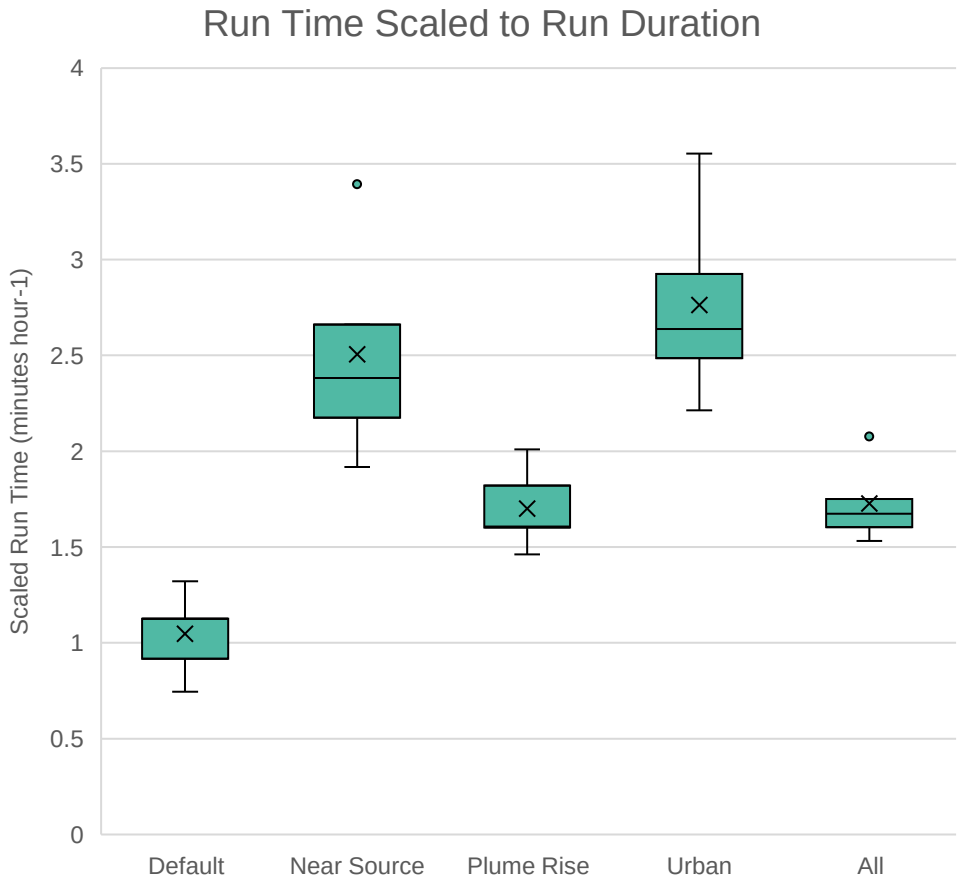

Appendix Figure A3: Box and whisker plot showing the distribution of model run times (minutes), scaled to the simulation durations (modelled hours) across all events for each of the set-ups. Run times are scaled to allow comparison across the case-studies. which are of varying simulation lengths. Boxes show the interquartile range (IQR), median and mean (cross), while the whiskers indicate the largest (smallest) scaling factor within 1.5 times the IQR of the third (first) quartile, with any values greater (smaller) than this marked as outliers

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